REMARKS

In the Final Office Action mailed February 12, 2007, the Examiner took the following action: (1) issued a requirement for information regarding AIAA-2001-1666; (2) rejected claims 1, 2, 6-9 and 11-12 under 35 USC §102(b) as being anticipated by Birchard (US 4751821); and (3) rejected claims 1-3, 5-9, 11-13, 26-28, 30-38, and 51-60 under 35 USC §102(b) as being anticipated by "An Advanced Buffet Load Alleviation System" (AIAA-2001-1666). Although the basis for the rejection of claim 10 has not been articulated, Applicant assumes for purposes of this response that claim 10 is rejected on the same grounds as claim 30. Applicants respectfully request reconsideration in view of the foregoing amendments and the following remarks.

I. Information Regarding AIAA-2001-1666

The Examiner has requested the following information regarding AIAA-2001-1666: (1) information regarding the testing of the device shown in AIAA-2001-1666; and (2) information regarding the actuators of the device shown in AIAA-2001-1666, how they are mounted, and how the device differs from Applicant's claims in the subject application. Submitted concurrently herewith as Attachment A is a declaration of the undersigned attorney, Dale Barr, including true and correct copies of documentation provided by inventor Dale Pitt that is responsive to the Examiner's request for information. Together with the Remarks provided in Section II below regarding Burnham (AIAA-2001-1666), Applicant respectfully submits that the Examiner's request for information regarding AIAA-2001-1666 has been satisfied.

II. Rejections Under §102(b)

Claims 1, 2, 6-9 and 11-12 stand rejected under 35 USC §102(b) as being anticipated by Birchard (US 4751821), and claims 1-3, 5-9, 11-13, 26-28, 30-38, and 51-60 (and claim 10) stand rejected under 35 USC §102(b) as being anticipated by "An Advanced Buffet Load Alleviation System" (AIAA-2001-1666).

Claims 1-3 and 5-13

As amended, claim 1 recites:

> 1. A hybrid actuator for actuating a component, comprising:
> a first actuator configured to be coupled to the component and to move the component a first actuation distance;
> *a second actuator approximately aligned with and coupled to the first actuator by a linkage*, the second actuator being configured to move the component a second actuation distance via the linkage and the first actuator, *wherein the first actuator operates within a first frequency range and the second actuator operates within a second frequency range, the first frequency range including a first vibrational mode of the component and the second frequency range including a second vibrational mode of the component*, and wherein the linkage is configured to combine the first actuation distance and the second actuation distance to move the component a third actuation distance. (emphasis added).

Birchard (US 4751821)

Birchard teaches a digital linear actuator that includes a plurality of digital actuator cells each connected to the next in sequential fashion. (5:52-55). A controller 3 transmits signals to the actuator cells 2-x, causing them to contract or expand. (6:17-35). According to Birchard, the digital linear actuator is configured to simulate the behavior of a muscle in a prosthetic or robotic device. (3:7-12).

Applicant respectfully submits that Birchard fails to disclose, teach, or fairly suggest the hybrid actuator recited in claim 1. Specifically, Birchard fails to teach or

suggest a hybrid actuator that includes, in relevant part, a first actuator, *a second actuator approximately aligned with and coupled to the first actuator by a linkage, ... wherein the first actuator operates within a first frequency range and the second actuator operates within a second frequency range, the first frequency range including a first vibrational mode of the component and the second frequency range including a second vibrational mode of the component.* (emphasis added). Birchard is silent as to the frequency of operation of the digital actuators 2-x. Birchard doesn't teach or suggest that the digital actuators 2-x operate at different frequencies, and particularly does not teach or suggest a first actuator operating within a first frequency range that includes a first vibrational mode of the component, and a second actuator operating within a second frequency range that includes a second vibrational mode of the component.

<u>Burnham (AIAA-2001-1666)</u>

Burnham teaches an advanced buffet load alleviation system. According to Burnham, as best shown in Figure 2, a plurality of piezoelectric actuators are coupled to an upper portion of an outer skin of a vertical tail of an aircraft, and a rudder actuator is coupled to a rudder situated near a base of the vertical tail. (p. 3, col. 1). The rudder actuator is used to control bending of the tail, while the piezoelectric actuators are used to control torsion of the tip of the tail. (p. 3, col. 1, para. 2).

Burnham fails to disclose, teach, or fairly suggest the hybrid actuator recited in claim 1. Specifically, Burnham fails to teach or suggest a hybrid actuator that includes, in relevant part, a first actuator, *a second actuator approximately aligned with and coupled to the first actuator by a linkage, ... wherein the first actuator operates within a first frequency range and the second actuator operates within a second frequency range,*

the first frequency range including a first vibrational mode of the component and the second frequency range including a second vibrational mode of the component. (emphasis added). Burnham, is silent as to a linkage between the piezoelectric actuators and the rudder actuator, and Burnham further teaches that these actuators are spaced apart rather than approximately aligned as recited in claim 1.

For the foregoing reasons claim 1 is allowable over Birchard and Burnham. Claims 2-3 and 5-13 depend from claim 1 and are allowable at least due to their dependencies on claim 1, and also due to additional limitations recited in those claims.

<u>Claims 26-28 and 30-38</u>

As amended, claim 26 recites:

> 26. A system for suppressing undesired movement of a component, comprising:
>
> at least one motion sensor configured to monitor the component;
>
> a processor linked to the at least one motion sensor, the processor configured to accept an input from the at least one motion sensor, and to control a plurality of actuators responsive to the input from the at least one motion sensor;
>
> a first actuator controlled by the processor, the first actuator connected to the component, the first actuator configured to move a first actuation distance at a first range of frequencies;
>
> a second actuator controlled by the processor, the second actuator connected to the component, *the second actuator approximately aligned with and coupled to the first actuator by a linkage*, the second actuator being configured to move a second actuation distance at a second range of frequencies, *wherein the first range of frequencies includes a first vibrational mode of the component and the second range of frequencies includes a second vibrational mode of the component, and wherein one of the first and second actuators comprises a hydraulic actuator, and the other of the first and second actuators comprises a piezoelectric actuator.* (emphasis added).

For the reasons set forth above, Birchard and Burnham fail to disclose, teach, or fairly suggest the system recited in claim 26. Specifically, the cited references fail to

teach or suggest a system having a hybrid actuator that includes, in relevant part, a first actuator, *a second actuator approximately aligned with and coupled to the first actuator by a linkage, ... wherein the first range of frequencies includes a first vibrational mode of the component and the second range of frequencies includes a second vibrational mode of the component, and wherein one of the first and second actuators comprises a hydraulic actuator, and the other of the first and second actuators comprises a piezoelectric actuator*. (emphasis added). Therefore, claim 26 is allowable over the cited references, and claims 27-28 and 30-38 are allowable at least due to their dependencies on claim 26.

Claims 51-60

As amended, claim 51 recites:

> 51. An aircraft with hybrid motion suppression, comprising:
> a fuselage including an appendage;
> at least one motion sensor adapted to sense motion of the appendage;
> a processor linked to the at least one motion sensor, the processor adapted to accept an input from the at least one motion sensor, and to provide at least one output signal responsive to the input from the at least one motion sensor;
> a first actuator controlled by the processor, the first actuator connected to the appendage, the first actuator configured to receive the at least one output signal and to move a first actuation distance to oppose the undesired movement at a first range of frequencies, *the first range of frequencies including a first vibrational mode of the appendage*;
> a second actuator controlled by the processor, *the second actuator approximately aligned with and coupled to the first actuator by a linkage*, the second actuator configured to receive the at least one output signal and to move a second actuation distance to oppose the undesired movement at a second range of frequencies, *the second range of frequencies including a second vibrational mode of the appendage*; and wherein
> the linkage is configured to combine the first actuation distance and the second actuation distance thereby moving at least a portion of the appendage a third actuation distance in opposition to the undesired movement. (emphasis added).

For the reasons set forth above, Birchard and Burnham fail to disclose, teach, or fairly suggest the aircraft recited in claim 51. Specifically, the cited references fail to teach or suggest an aircraft having a hybrid actuator that includes, in relevant part, a first actuator connected to the appendage, the first actuator configured to receive the at least one output signal and to move a first actuation distance to oppose the undesired movement at a first range of frequencies, *the first range of frequencies including a first vibrational mode of the appendage, a second actuator approximately aligned with and coupled to the first actuator by a linkage*, ... the second actuator configured to receive the at least one output signal and to move a second actuation distance to oppose the undesired movement at a second range of frequencies, *the second range of frequencies including a second vibrational mode of the appendage*. (emphasis added). Therefore, claim 51 is allowable over the cited references, and claims 52-60 are allowable at least due to their dependencies on claim 51.

CONCLUSION

For the foregoing reasons, Applicants respectfully submit that claims 1-3, 5-13, 26-28, 30-38, and 51-60 are now in condition for allowance. If there are any remaining matters that may be handled by telephone conference, the Examiner is kindly invited to contact the undersigned attorney at the telephone number listed below.

Respectfully Submitted,

Dated: May 14, 2007

By: Dale C. Barr

Dale C. Barr
Lee & Hayes, PLLC
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206-315-7916

Enclosures: Attachment A. Declaration of Dale Barr Providing Information regarding AIAA-2001-1666 (including Exhibits A and B)

Attachment A. Declaration of Dale Barr Providing Information regarding AIAA-2001-1666

I, Dale C. Barr, certify and declare as follows:

1. I am over twenty-one years of age and have knowledge of, and am competent to testify to, the facts stated herein. I am the attorney of record in the above-captioned patent application.

2. Attached hereto as Exhibit A is a true and correct copy of a document entitled "Reply to BA9665" submitted to me by inventor Dale Pitt in partial satisfaction of the Examiner's request for information regarding AIAA-2001-1666. The term "BA9665" is an arbitrary name assigned to the Final Office Action dated February 12, 2007 by this law firm's document management system.

3. Attached hereto as Exhibit B is a true and correct copy of a document entitled "Design and Modelling of an Advanced Buffet Load Alleviation System for a Fighter Aircraft Vertical Tail" submitted to me by inventor Dale Pitt in partial satisfaction of the Examiner's request for information regarding AIAA-2001-1666.

I certify and declare under penalty of perjury under the laws of the State of Washington and the laws of the United States that the foregoing is true and correct to the best of my knowledge and belief.

DATED this 14th day of May, 2007, at Bremerton, Washington.

Dale C. Barr

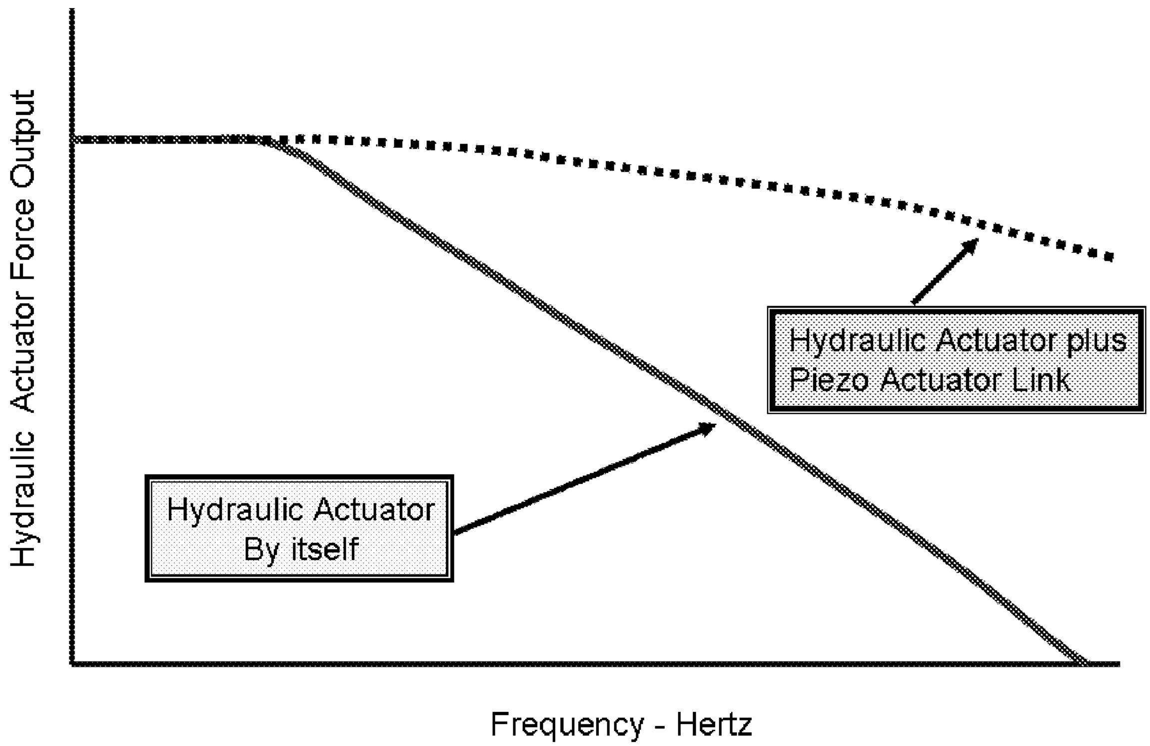
Dale C. Barr, Reg. No. 40,498

Reply to BA9665

The American Institute of Aeronautics and Astronautics (AIAA) paper, "An Advanced Buffet Load Alleviation System", was presented at 42nd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference which was held in Seattle Washington from 16-20 April 2001. This paper presented results of a Boeing design study to suppress aerodynamic vibrations of an aircraft vertical tail. Figure 2 of the paper on page three shows that the vibration suppression system is made up of two separate systems. One system is the hydraulic rudder actuator that is used to suppress the low frequency modes. The second system suppresses the higher frequency modes by using a series of "Flat Piezo Actuators" that are attached with adhesive externally to the vertical tail skins. Each "Flat Piezo Actuator" was 2.25 inches wide, 3.35 inches long and 0.1 inch thick. There were twenty-three of these flat actuators that were glued to the skins. A subsequent paper was written that described these actuators and their testing. This paper is entitled, "Design and Modeling of an Advance Buffet Load Alleviation System for a Fighter Aircraft Vertical Tail" RTO-MP-AVT-123 Symposium Paper #23. It was presented at "Flow-Induced Unsteady Loads and the Impact on Military Applications" Symposium which was held in Budapest Hungary from 25-28 April 2005. Figure 3, Figure 7 and Figure 9 of this paper has photographs of these "Flat Piezo Actuators" that were used on the test. Twenty-three of "flat Piezo Actuators" were glued on each of the outside surfaces of the vertical tail (on the outboard side and inboard side of the vertical tail). Thus, a total of forty-six actuators were used in test. This system reduces the tail vibrations by inputting canceling strain energy into the vertical tail skins. The external actuators are not as effective as hoped and they have to be distributed on the outside surface affecting the aerodynamics of the tail.

The proposed hybrid actuator documented in the Patent Application does indeed solve the same problem, but in a different and more efficient fashion. Studies by Dr. Dale Pitt have shown that the aerodynamic control surface (rudder, aileron, etc.) which is used to reduce the low frequency vibrations, **could also reduce the high frequency vibrations ….. if the control surface could be oscillated at those higher frequencies.** The concept put fort in the patent application is to use the high frequency response characteristics of the Piezo materials in conjunction with the hydraulic actuator to provide a more efficient means of reducing the vibrations than the system shown in the paper AIAA-2001-16. The below figure shows that the typical hydraulic actuator force decreases with higher frequencies. The proposed patent uses piezo material that is manufactured in a thick stack or a column. The Piezo stack is placed inline with the actuator or is place on the end of a mechanical device that increases the displacement of the actuator link. The below figure shows that the proposed hybrid hydraulic/Piezo actuator will have more authority at the higher frequencies. Using the aerodynamic control surface weight to reduce aerodynamic vibrations is more effective, electrical power required and system weight, than using wafer or flat piezo actuators glued to the surface.

Exhibit A (10/825,920)



Design and Modelling of an Advanced Buffet Load Alleviation System for a Fighter Aircraft Vertical Tail

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ABSTRACT

This paper describes the design, modelling and testing of an advanced buffet load alleviation (BLA) system that utilizes distributed piezoelectric actuators in conjunction with an active rudder to reduce the structural dynamic response of the F/A-18A/B/C/D aircraft vertical tails to buffet loads. The BLA system was defined analytically with a detailed finite-element-model of the tail structure and piezoelectric actuators. Oscillatory aerodynamics were included along with a buffet forcing function to complete the aeroservoelastic model of the tail with rudder control surface. Two single-input-single-output (SISO) controllers were designed, one for the active rudder and one for the active piezoelectric actuators. The results from the analytical open and closed loop simulations were used to predict the system performance. The objective of this BLA system is to extend the life of vertical tail structures and decrease their life-cycle costs. This system can be applied to other aircraft designs to address suppression of structural vibrations on military and commercial aircraft. The analytical modelling of the piezoelectric actuators was validated in a mini tail test. A subscale test of a subset of piezoelectric patches installed on a vertical tail was conducted to validate the integration of two specially designed high power switch mode amplifiers with the piezo actuators. The final design of the control system was conducted on a full scale aircraft in a ground test at the Australian International Follow-On Structural Test Program (IFOSTP) facility.

1.0 INTRODUCTION

The capability of modern fighter aircraft to sustain flight at high angles of attack and/or moderate angles of

sideslip often results in immersion of part of the aircraft in unsteady, separated, vortical flow emanating from the aircraft's forebody or wings, Figure 1. The flow from these surfaces becomes turbulent and separated when the aircraft is flying at these conditions. This flow contains significant levels of energy over a frequency bandwidth coincident with low-order structural vibration modes of wings, fins, and control surfaces. The induced unsteady pressures that are applied to these lifting surfaces due to the turbulent flow are commonly referred to as buffet. The interaction of the buffet and the structure produces a structural-mode response known as buffeting. Prolonged exposure to the buffet loads has resulted in fatigue of structures on several aircraft. Damage to aircraft due to buffeting has led to redesigns of aircraft structure and increased support costs. For the F/A-18A-D aircraft, unsteady buffet loads from flight at high angle of attack (20 to 44 degrees) impinge on the vertical tails as shown in Figure 1. These buffet loads contribute to the fatigue of the vertical tail structure along with the steady aircraft maneuver loads.

Several passive methods have been investigated in an effort to reduce the buffet response and increase the fatigue life of vertical tails on military aircraft. One approach to solving this issue was to add passive damping material to the tails while they are being manufactured [1]. Another approach increased the bending stiffness of the tails [2]. The F/A-18A-D aircraft have additional structure added to the vertical tails in conjunction with a fence on the wing leading edge extension (LEX) that disperses the vortex prior to impinging on the vertical tail [3&4]. The additional structure, in combination with the LEX fence, produces a vertical tail that exceeded the fatigue requirements. These passive methods have been successful at reducing the buffet response of the vertical tails, but have increased the cost and gross weight of the vehicle.

Another method to reduce the buffet response incorporated an active control system that deflects the rudder in response to measured motion at the tip of the tail [5&6]. This method increases the fatigue life at most angles of attack through control of flexible mode 1 (F/A-18 vertical tail 1st bending) at 15 Hz. This method is limited to controlling the response of the structural modes within the rudder actuation bandwidth (< 20 Hz on F/A-18A-D aircraft). Therefore, it is not effective for reducing the fatigue damage from flexible mode 2 at 45 Hz (vertical tail tip torsion).

Investigations and tests of active control of the vertical tail vibration response using “smart” materials (piezoelectric actuators) distributed over the vertical tail structure has proven successful at reducing the overall buffet response [7&8]. A full scale test on the F/A-18 vertical tail with a piezoelectric actuator-based active control system was completed during 1997 and 1998 at the International Follow-On Structural Test Program (IFOSTP) facility in Melbourne, Australia [8]. The results from this test indicated that the piezoelectric actuators attached to the skin were more effective at reducing the response of mode 2 than mode 1.

The major drawback with using the piezoelectric actuators attached to the tail skin for controlling mode 1 arises from the strain energy distribution for this mode and the stiffness of the tail structure near the root. The finite element model predicted 40 percent of the modal strain energy for mode 1 in the under skin tail attachment fittings to the fuselage and 50 percent of the modal strain energy was in the tail skins. The piezoelectric actuators were ineffective near the tail root because of the large structural stiffness in the attachment fittings and thick skin. In contrast, the piezoelectric actuators were very effective for mode 2 because this mode had 60 percent of the modal strain energy in the tail skins and this strain energy was concentrated in the upper third of the vertical tail where the skin thickness was closer to a tenth of an inch.

Extensive research and testing has been completed in the past ten years on the development of an active BLA system for vertical tails of fighter aircraft as described previously. The results from this research identified two systems that have been effective at actively reducing the buffet response of a vertical tail. The first system

employed the rudder control surface to actively control the vertical tail dynamic response [5-7] and the second system utilized piezoelectric actuators attached to the skin [7&8]. NASA LaRC developed the combination of these two systems under the Scaling Influences Derived from Experimentally Known Impact of Controls (SIDEKIC) program [9].

The blended system of the rudder and piezoelectric actuator technologies [9] was selected for the design of the F/A-18 vertical tail buffet load alleviation system presented in this paper, Figure 2. The application of this combined system, in which the rudder actuator controls the response of the tail low frequency mode 1 and the piezoelectric actuators controls the higher frequency mode 2, used the most effective features of each system. The major components of the active BLA system are shown in Figure 2. The blended actuator system includes a separate single-input, single-output (SISO) controller for each system. The existing aircraft rudder actuator and servo system was combined with a SISO controller, sensors and signal conditioner to complete the active rudder system. The piezoelectric actuator system was similar except that the switch mode amplifier, which was connected to the aircraft power supply, drives the piezoelectric actuators. Both systems utilize the response of the two accelerometers and strain gage shown in Figure 2. Boeing conducted system modelling and design studies to verify the control authority of the rudder actuator and the piezoelectric actuators for buffet load alleviation for the F/A-18 A/B/C/D vertical tails [10].

The objective of the BLA system design was to reduce the buffet response of the F/A-18 vertical tail and extend the operational life of the structure. The BLA system performance goal was established as a 25 percent reduction in the buffet response at the fatigue critical condition. The fatigue critical condition was not the condition of peak buffet response but was determined from the combination of buffet response and aircraft usage. This combination produced fatigue damage tables, which identify the critical fatigue condition for each vibration mode of the vertical tail.

The analytical performance objective was doubled from 25 percent to 50 percent reduction at the fatigue critical condition to account for differences between the analytical representation and the actual hardware of the BLA system [9]. The use of free strain parameters for the piezoelectric actuators leads to over predicting the performance along with unaccounted for losses due to stacking the actuators and the general nonlinear behaviour of the piezoelectric actuators [9]. Also, the analytical representation of the rudder aeroservoelastic model tends to over predict the rudder effectiveness [5].

2.0 ANALYTICAL SYSTEM MODELLING AND DESIGN

The F/A-18 vertical tail structure was modelled with a detailed NASTRAN plate/shell finite element model. The detailed model included the skin elements, spars and ribs. The model was cantilevered with attachment springs along the root to represent the compliance of the aft fuselage. The rudder was modelled along the rudder elastic axis with bar elements and attached to the vertical tail with a rotational spring, which represents the rudder actuator. A comparison of the normal modes measured to predicted frequencies are presented Table 1. The analytical-to-measured percent difference in frequency was less than 3 percent for the buffet critical modes 1 and 2. The modal equations for aeroelastic response were used to develop a state space representation of the buffet load alleviation (BLA) system, similar to previous research [5-8]. The total degrees of freedom of the structural dynamic equations of motion for a flexible structure were greatly reduced by transforming the equations from physical coordinates, xyz, to modal coordinates, q. Several controllers were designed and analytical simulations were completed to evaluate the BLA system. The modelling tools used at Boeing in the F/A-18 Structural Dynamics group were utilized to complete this task, namely NASTRAN for structural modelling, N5KM (doublet lattice) for aerodynamic modelling [11], FAMUSS for aeroservoelastic modelling [12], MATLAB® and SIMULINK for controller design and system simulation. The modelling process and

preliminary control law development is described in more detail in [10]. However, a brief summary will be presented in this paper. The unsteady aerodynamics of the vertical tail were represented using a linear doublet lattice computer code, N5KM [11]. The unsteady aerodynamic forces on the tail result from the tail vibratory motion and are not to be confused with the buffet aerodynamic force on the tail. The unsteady aerodynamic forces on the tail were transformed from physical coordinates, xyz, to modal coordinates, q. The NASTRAN vibratory mode shapes, φ, were combined with the unsteady Aerodynamic Influence Coefficient (AIC) to generate generalized aerodynamic forces at a series of reduced frequencies (k=ωb/V; where ω=oscillatory frequency, b=semi-chord, and V=Velocity). These generalized aerodynamic forces were combined with the generalized mass, M, and generalized stiffness, K. The buffet aerodynamic force on the vertical tail was modelled with a similar approach as used in previous research [8]. The buffet force, $F_{buf}(t)$, was modelled as a Gaussian white noise process with shaping filters and was applied to the vertical tail model at the same location as the IFOSTP shaker attachment [8]. The shaping filters were scaled to match measured response from flight test data for the six flight conditions analyzed [10]. The modal force from the piezoelectric actuators, F_{piezo}, was determined from the analytical actuation of the piezoelectric elements on the vertical tail model. The model was loaded with a delta temperature across the piezoelectric elements that produced a specified strain in these elements. The resulting grid point forces in the model were multiplied by the corresponding vibration mode shape for each degree-of-freedom to determine the piezoelectric modal force, F_{piezo}. The next step was the addition of the aeroservoelastic model for rudder control. Because the vertical tail structural modes were excited by the rudder control surface deflections, the equations of motion were re-written to account for the aircraft control surface deflections. The control surface inertia effects, M_c, and aerodynamic effects, $Q_c(k)$ were included along with the commanded rudder input U(t). The modal equations of motion were written as a transfer function frequency response in the Laplace domain as given by equation 1. This is the technique used in FAMUSS [12]. This produces the modal transfer function response of the modal coordinates for a rudder input, buffet force input, and piezoelectric actuator input, where s=jω and k=ωb/V.

$$H_q(s) = \frac{q(s)}{u(s)} \tag{1}$$

$$H_q(s) = \left[Ms^2 + K(1+jg) - \frac{1}{2}\rho V^2 Q(k) \right]^{-1} \bullet \left[-M_C s^2 + \frac{1}{2}\rho V^2 Q_C(k) + F_{buf} + F_{piezo} \right] \tag{2}$$

The modal transfer function is transformed to the physical coordinate system using the vibratory mode shapes, φ. The transfer function in the physical coordinates is given by equation 3.

$$H(s) = \frac{y(s)}{u(s)} = \frac{\phi_C\, q(s)}{u(s)} = \phi_C H_q(s) \tag{3}$$

A separate transfer function is calculated for each input-output pair. FAMUSS was used to create an equivalent state space model of the transfer function that was used in the subsequent time domain transient analysis, SIMULINK. The state space equations were written as:

$$\hat{H}(s) = C\left[sI - A\right]^{-1} B + D \tag{4}$$

FAMUSS [12] used a nonlinear optimization technique to determine the individual terms of the state matrices A, B, C, and D to fit the transfer function response at each tabulated frequency, ω. The resulting aeroservoelastic state space model from FAMUSS had three inputs: 1) rudder rotation, 2) buffet force, and

3) piezoelectric actuator force.

The state space model was incorporated into the MATLAB® SIMULINK toolbox and time history simulations of the vertical tail buffet response were completed. The design of the rudder and piezoelectric controllers were also completed in SIMULINK.

Vert. Tail Mode Description	Analytical Freq. - Hz	Measured Freq. - Hz	Percent Difference
1 - 1st Bending	15.3	15.3	0.0
2 - Tip Torsion	44.7	46.0	-2.8
3 - Rudder Rot.	49.6	49.6	0.0

Table 1 Analytical and Measured Frequency

The FEM 2nd mode strain energy densities were used to determine the location of the piezoelectric actuators. A shaded contour of the strain energy density for Mode 2 is displayed in Figure 2 for the model skin elements. This contour reveals the strain energy is in the upper half of the vertical tail skin and the highest densities are in the upper third. A photograph of the final piezoelectric actuator distribution is also shown in Figure 2.

The buffet aerodynamic force was modelled with a Gaussian white noise process and shaping filter to match the response of measured flight test data [8]. This force was analytically modelled as a point force coinciding with the IFOSTP shaker attachment location, intersection of the vertical tail mid-rib and 46 percent spar. The buffet force of unit magnitude was added to the BLA system equations of motion as an input quantity varying with time, $F_{buf}(t)$. The fatigue damage of the F/A-18 vertical tail is based on the band-pass filtered response for mode 1 (10-20 Hz) and mode 2 (32-52 Hz) of the vertical tail aft-tip accelerometer KS16 [3,4].shown in Figure 2. The buffet force analytical shaping filters were scaled to produce the G's RMS response from the measured flight test data.

The rudder actuator model represents the commanded input and output of the rudder hydraulic actuator. The commanded rudder produces both aerodynamic and inertia forces. The two forces when plotted as a function of frequency showed [10] that the inertia forces increased with frequency and the aerodynamic force decreased with frequency. The crossover frequency is about 7 Hz. For frequencies less than 7 Hz, the aerodynamic component comprised the majority of the commanded rudder force and for frequencies above 7 Hz, the commanded rudder inertia force dominated. The use of the rudder to suppress the first flexible mode during a ground test was valid, because the majority of the rudder control force was inertia.

3.0 PRELIMINARY CONTROLLER DESIGN

Numerical simulations were conducted using the analytical models of the tail, rudder actuator and piezoelectric actuators to verify buffet load alleviation. The control laws were developed independently as single-input, single-output (SISO) for the rudder to control mode 1 at 15 Hz and the piezoelectric actuators to control mode 2 at 45 Hz. The feedback sensor for each control law was selected as the vertical tail aft tip acceleration. The complete analytical model of the BLA system was incorporated into the MATLAB® SIMULINK toolbox where both open and closed loop time history simulations were completed to determine the system performance. The final analysis was completed with both the piezoelectric and rudder actuator

control systems active. The performance from the combined condition was better than the individual conditions because of the improved isolation for each feedback controller. The results for the critical mode 2 condition with combined control are displayed in Figure 4. Also included at the bottom of this figure are the commanded inputs for the piezoelectric (top) and rudder (bottom). The overall performance of the combined feedback control system produced 70 percent to 30 percent vertical tail buffet response reductions for flight conditions ranging from moderate to severe buffet. This was accomplished with a maximum commanded rudder position of ±2 degrees (15 Hz) and about 10 lbs of piezoelectric actuators operating at a peak power level of 2000 Watts.

4.0 SUBSYSTEM GROUND TESTING

A series of ground test were performed to validate the Buffet Load Alleviation concept. These tests included small building block test for the piezoelectric actuator development and culminated with a full scale ground test of the F/A-18 vertical tail in simulated buffet conditions.

NASA LaRC developed the MFC piezoelectric actuators used for the full scale ground test. NASA tested various actuator ply lay-ups and orientations on aluminium beams [13, 14, & 15]. Analytical models were developed by Boeing to support the NASA LaRC MFC actuator development, one such model is shown in Figure 5. The analytical model was for a 3 inch by 9 inch aluminum plate with the MFC, 2.25 inches by 3.375 inches, analytically modeled using the static thermal analogy. The thermal proprieties were used to represent the actuators electrical response. The aluminum plate free-free first bending mode was 51 Hz which is similar to the frequency of interest to be controlled on the F/A-18 vertical tail. NASA tested actuators of varying thickness and varying ply lay-ups [15]. A comparison of the measured strain produced by these actuators on the aluminum beam with the predicted response is shown in Figure 6. The number of piezo layers (horizontal axis) was varied from 1 to 7 and the measured strain for the oscillatory response is plotted on the vertical axis. A stain gage was mounted on lower surface of aluminum beam centered under the actuator. An oscillating voltage of 1900 volts peak to peak was applied to the "Combined Actuator". The test objective was to determine the maximum practical number of layered actuators before the actuated strain started to diminish. The measured maximum oscillator strain is plotted as "Solid" lines. The predicted results from NASTRAN are plotted as "Dashed". The "circle" symbols are for a 7 mil thick actuator. The squares are for a 9 mil thick actuator and the "Triangles" are for a 15 mil actuator. Sinusoidal voltages were applied at 1 Hz and 10 Hz. Test data had considerable scatter, but generally followed the predicted trend. The final design of the actuators for the full scale ground test in Australia was selected to be 9 layers of 7 mil thick ceramic fibers oriented at 45 degrees to the longer edge of the actuator package. This selection was based on ease of manufacture and the above test results.

4.2 Mini Tail Test

The finalized actuator design was tested on a representative tip section of the F/A-18 vertical tail. The Mini Tail Test Specimen (MTTS) was manufactured from representative composite skins and aluminum spar. The skin and spar sizes represent the actual size at the tail tip. The test was designed to verify that the piezoelectric actuators had actuator authority to excite the tail 2nd mode. The steel bar size and mass was designed to yield the target Frequencies, 45 Hz Torsion (Tail 1st Torsion) and 65 Hz Bending (Tail 2nd Bending). A 250 pound shaker was attached to the MTTS, and was used to drive the tail to representative strain levels that the real tail experienced in flight. The photograph of the MTTS during testing is shown in Figure 7. Three response accelerometers were mounted to the fixture. A test was conducted to verify the Piezo electric actuators ability to reduce buffet loads. The MTTS was driven with a sine excitation of 35 Hz at force levels that yielded a tip

response of ± 3.5 g's. As shown in Figure 8, the MFC actuators when operated with a simple gain and phase control law reduced the tip response to ± 1.2 g's (66 percent reduction). The attachment of the heavy shaker to the MTTS (armature mass) resulted in the torsional frequency of the MTTS being lowered from 45 Hz to 35 Hz.

4.3 Switch Mode Amplifier Bench Test

Two high power switch mode amplifiers were designed and built by Boeing for the full scale ground test [16]. Linear power amplifiers dissipate more than twice the energy that is transferred to the piezos, and this inefficiency increases linearly with increasing frequency. The Boeing designed switch mode amplifiers were more efficient and smaller than the traditional amplifier. A subsystem test of the two switch mode amplifiers and a subset of piezoelectric actuators were planned prior to testing in Australia. This test was performed as a risk mitigation test prior to shipping all the equipment to Australia. Six actuators, of the planned 23, were placed on each side of a spare vertical tail that was owned by NASA LaRC. The tail was mounted on a series of soft springs designed to yield the correct 1st bending and 1st torsional frequencies of the tail. A single shaker was attached to the top of the tail to excite the 1st torsional mode. The amplifiers were able to drive the piezo at full power (±1500 volts) at 45Hz. A photograph of the test set-up is shown in Figure 9. Additionally, NASA LaRC's DSPACE control system was employed to verify the preliminary piezo control laws. The tail was driven in a 45Hz sine as shown in Figure 10. The reference accelerometer that was used for the design studies (KT16) was used as a feedback signal. Figure 10 is a plot of KT16's time history response. The plot shows when the controller is turned off that the response grows from ±2 g's to ±3 g's. No attempts were made at this time to optimize the controller.

All of the ground testing systematically verified the components that were to be employed in the full scale ground test in Australia.

5.0 FULL SCALE GROUND TESTING

The full-scale test article was the vertical tail on an F/A-18A structural test article that was inserted into the International Follow-On Structural Testing Project (IFOSTP) facility at Defence Science and Technology Organization (DSTO) in Melbourne, Australia. The IFOSTP test rig has the ability to generate flight representative static and dynamic loads on the airframe including maneuver loads. The buffet loads were applied to the vertical tail using two high-powered high displacement electrodynamic shakers. The tails were driven at force levels that resulted in vibratory tail strains and accelerations comparable to levels measured in previous flight tests. The flight conditions simulated by the test rig were maximum buffet fatigue levels and maximum buffet response for bin #1 (tail first bending mode at 15 Hz) and bin #2 (tail tip torsion mode at 45 Hz). The maximum buffet fatigue level is the condition, shown by usage that inflicted the most fatigue damage on the tail. This flight condition is less severe than the maximum buffet response flight conditions, which were the largest levels measured.

5.1 Open Loop Test

Open loop testing was conducted on the tail in the IFOSTP facility in Aug 2003. The testing concentrated on performing system identification testing for the rudder actuator and the piezoelectric actuators. The objectives of the open loop test were to verify the operation of the hydraulically powered rudder actuator, switch mode amplifier, and Macro Fiber Composite (MFC) actuators. The test also determined the response of numerous strain gages and accelerometers under the buffet environment simulated with the shakers, the output

characteristics of the rudder and piezoelectric actuators. Accelerometers and strain gauges were distributed over the tail [17]. Transfer functions , magnitude and phase angles, were generated for the rudder and piezo inputs. Figure 11 is a plot of the flight test accelerometer (KT16) transfer function magnitude for a sine sweep for the MFC actuators. The piezoelectric were subjected to sine sweeps from 5 Hz to 100 Hz. The NASA MFC actuators displayed excellent high frequency response. During the open loop testing, the two large shakers were seen to change the vertical tail frequency and damping characteristics. This was similar to the experience of previous testing [8]. The shaker characteristics are indicated by the difference between the transfer functions with the shakers attached (blue line) and with the shaker removed (green), as plotted in Figure 11. The two shakers changed the frequency of the tail and applied damping that reduced the height of the peak response. The peak response for the 48 Hz tip torsion mode is much larger and sharper for the case with the shaker removed. The MFC actuators were shown to be effective on the 91 Hz mode. The piezoelectric actuators also excited the first bending mode at a low level, 15 Hz shaker removed and 22 Hz shaker attached. An example of the rudder magnitude transfer function is shown in Figure 12. Once again the output is the KT16 accelerometer and the input is the rudder actuator voltage. The rudder input force was strictly its inertia force, as discussed previously. The figure shows that the rudder was capable of exciting the 12 HZ stabilator mode at low levels and the vertical tail first bending mode at 15 Hz. Attaching the shaker resulted in the damping and shaker mass changing the basic tail vibratory response. The rudder actuator was sent a command signal of a sine sweep from 5 Hz to 20 Hz. The vertical tail rudder rotation mode, at 28 Hz, was easily excited by the rudder actuator and was avoided in the sweep and is not shown in the plot. The system identification models from the open-loop testing were used to develop buffet reduction control laws that were tested during the closed loop ground test in the fall of 2004.

5.2 Closed Loop Test

The final ground test validation of the Buffet Load Alleviation (BLA) was a closed loop test that was conducted at the IFOSTP facility in August of 2004. The test consisted of testing various control laws designed by a host of engineers from different facilities [17]. The various control law strategies and their effectiveness is discussed in another paper at this conference [17]. A power spectral density (PSD) plot for the closed loop testing shows a representative level of reduced vertical tail response achieved as a result of the BLA system is shown in Figure 13. Overall spectral reduction showed a 1 g rms from BLA operative. Most of the reduction occurred at the two primary modes (16 and 49 HZ) of interest.

6.0 CONCLUSIONS

The design, modeling and ground test of an active hybrid buffet load alleviations system is discussed. The BLA system utilized the rudder actuator to control the F/A-18A 15 Hz vertical tail first bending mode. The rudder actuator did not have the authority (bandwidth) to control higher frequency modes above 20 Hz. A set of 23 NASA LaRC developed MFC piezo actuators were bonded to each side of the vertical tail tip to control the 45 Hz vertical tail first torsion mode. A series of actuator and switch mode amplifier tests were conducted to verify operation and reduce program risk prior to the full scale ground test of an F/A-18A in the Defence Science and Technology Organization's IFOSTP facility. The full scale ground test verified that buffet loads on a vertical tail can be reduced using the BLA active hybrid control system. The active piezoelectric actuation subsystem of the BLA System has been reduced in size and could be incorporated on a flight test aircraft. Additional reduction in size is still necessary before the hybrid BLA system could become operational. The active rudder subsystem is the closest to being implemented. This implementation is contingent upon further system level design and successful subsystem test.

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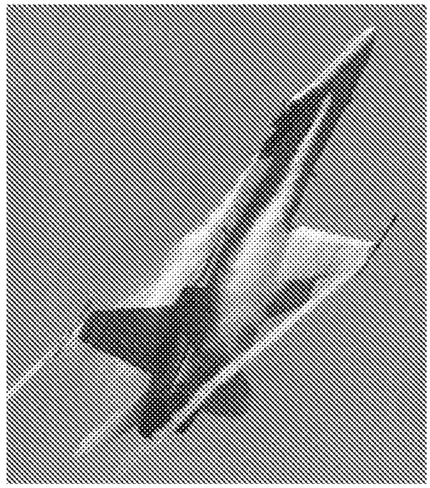

Figure 1. High-Performance Aircraft at High Angle of Attack

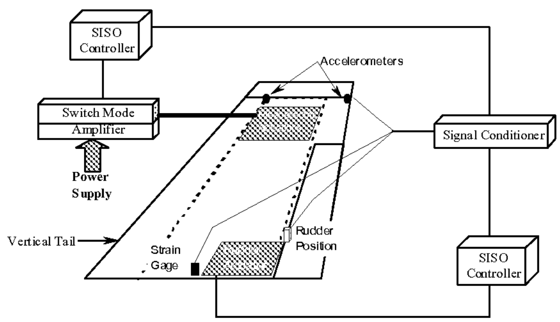

Figure 2. Major Components of BLA System

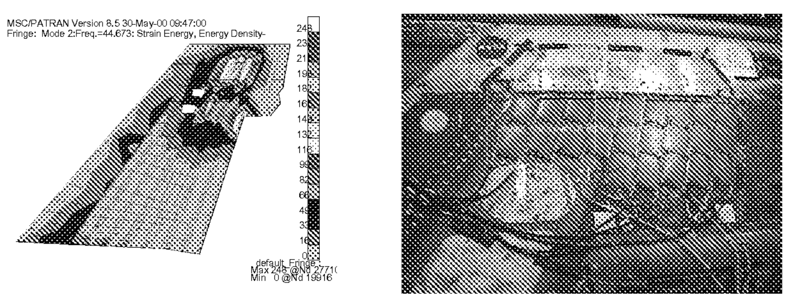

Figure 3. Mode 2 Strain Energy Density and

Piezoelectric Actuator Attachment Area

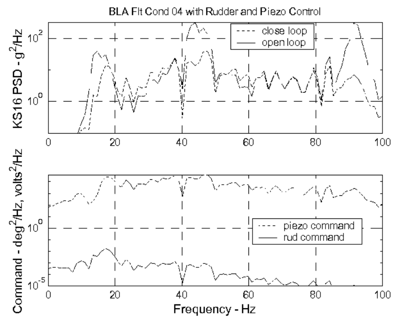

Figure 4. Closed Loop Analyses for Piezo-Rudder Control

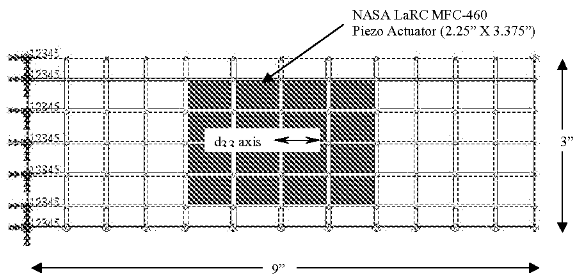

Figure 5. Analytical Model to Predict NASA-LaRC MFC Actuator Development Test

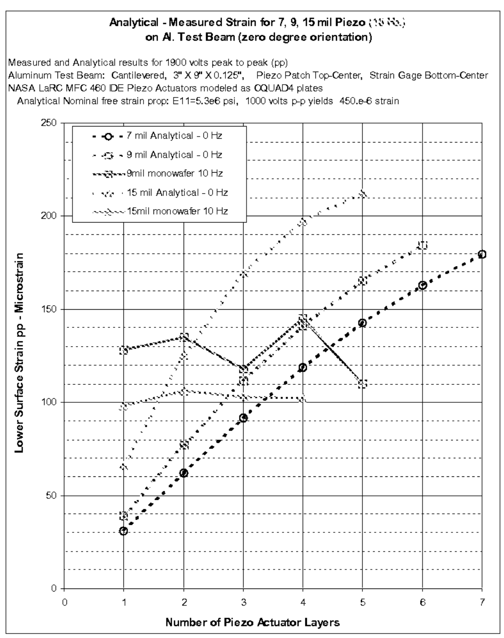

Figure 6. Piezo Actuator Development Testing, Measured and Analytical Results

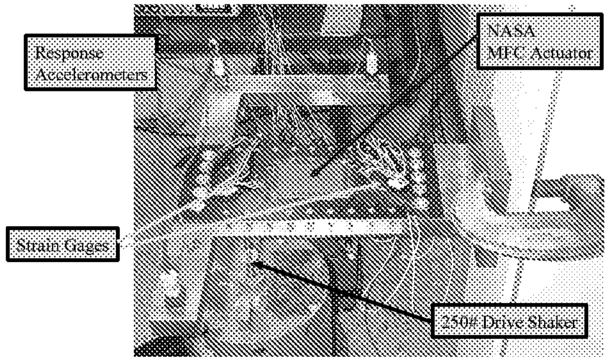

Figure 7 Boeing Mini Tail Test Specimen (MTTS)

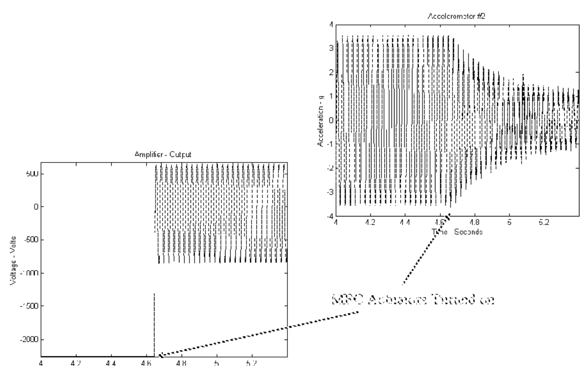

Figure 8. MTTS Reduced Response with Active Control

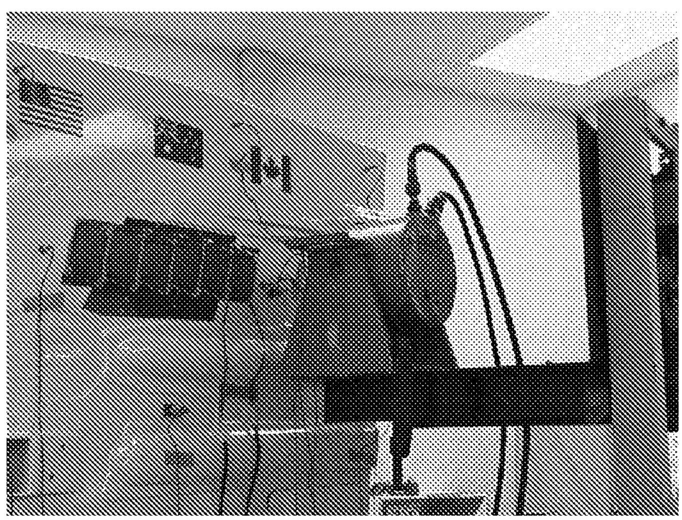

Figure 9. NASA LaRC Subsystem Test Set-Up

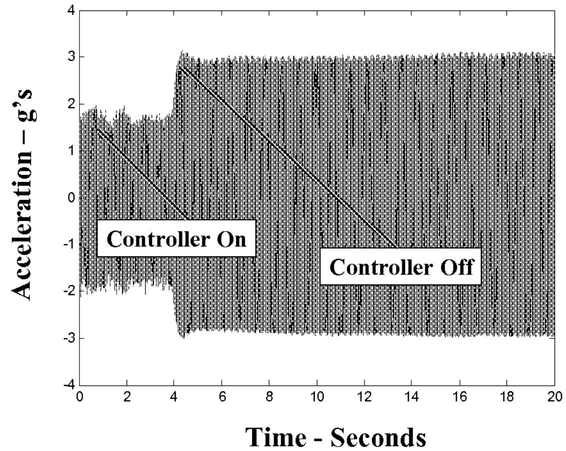

Figure 10. NASA LaRc Subsystem Response With Active Piezo Control

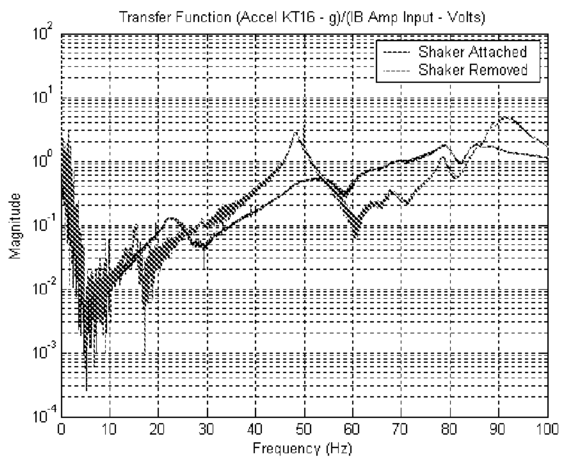

Figure 11. IFOSTP Open Loop Transfer Function – Piezo Actuator Input

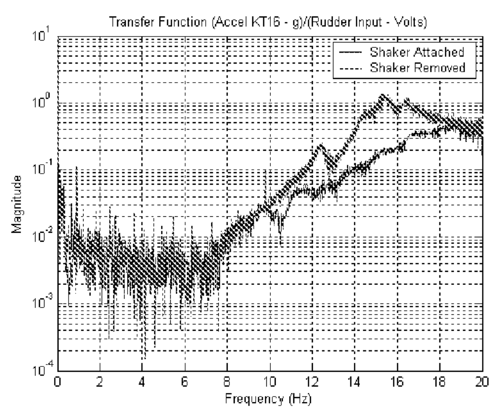

Figure 12. IFOSTP Open Loop Transfer Function – Rudder Input

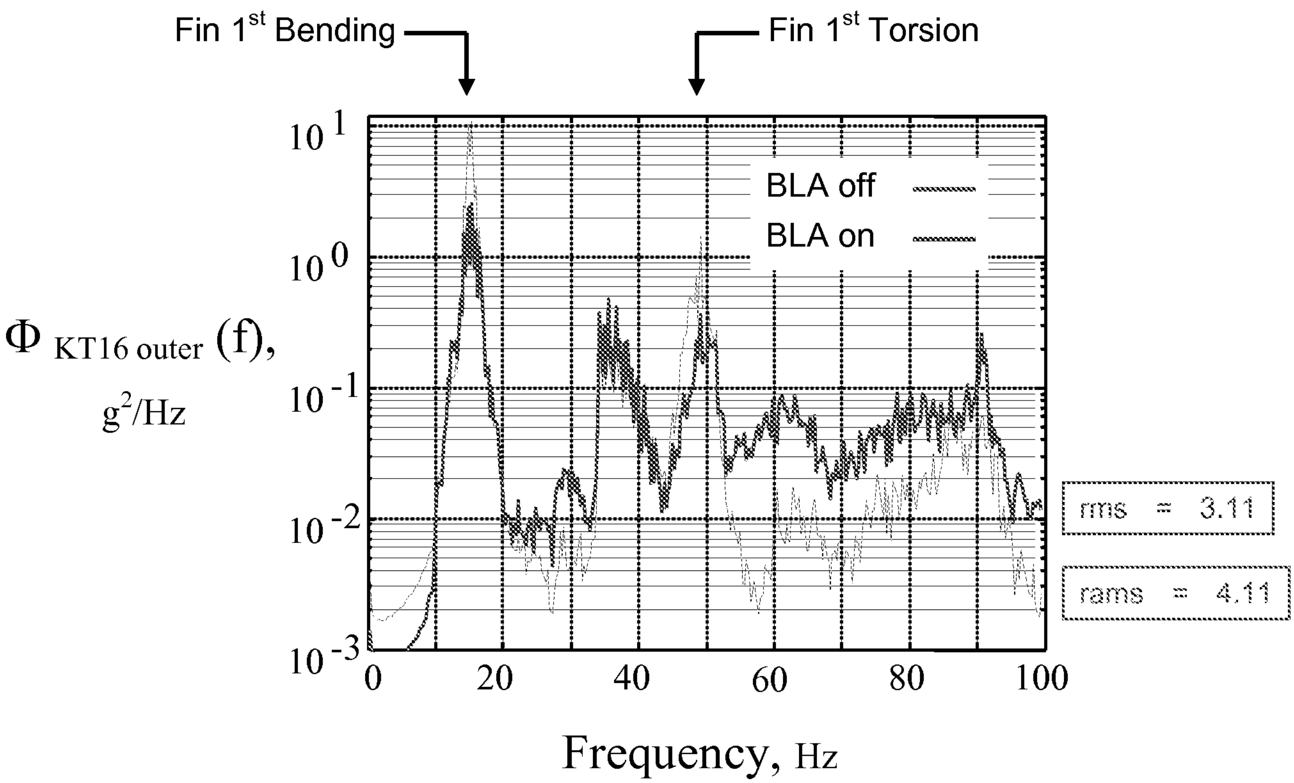

Figure 13. Representative Closed Loop Buffet Reduction